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For

Downhole Tool Controller Using Autocorrelation of Command Sequence

By

Kenneth R. Goodman

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Jeanne Colyland

Downhole Tool Controller Using Autocorrelation of Command Sequences

Background

[0001] Field of Invention. The present invention pertains to controllers of downhole tools used in subsurface well completions, and particularly to remotely actuated controllers.

[0002] Related Art. It is often desired to control downhole tools and equipment from the surface without using a dedicated communication medium, such as a wire, tube, or fiber optic cable. Whenever an existing medium such as drill pipe or wellbore fluids can be used, operating a downhole tool or device can be simplified and cost reduced.

[0003] Some prior art controllers that use such an existing medium use a set of predefined pressure sequences or expected pressure profiles programmed into a processor or other memory device to identify an actuation command sent from a remote location. The controller monitors pressure variations in the medium. Such variations may be monitored continuously or sampled discreetly. By comparing the received waveform with the reference pressure pulses, the controller is able to discriminate between noise and a command signal. When a command signal is detected, the controller responds by actuating a downhole device.

[0004] In wells with open perforations, it is sometimes difficult to send signals to a controller that uses predefined pressure sequences as a reference. To produce a response from the controller, the controller must receive pressure signals that match those pre-programmed pressure sequences within certain ranges of amplitudes and with changes at appropriate rates. Open perforations make it difficult or impossible to transmit and receive such sequences due to the wide variations in formation pressure, porosity, well fluids, and permeabilities normally encountered in a well.

Summary

[0005] The present invention provides for an apparatus and method to control a downhole tool remotely based on the autocorrelation of command sequences. Repeating signals of *a priori* unknown or undefined shape can be correlated to themselves to reliably distinguish intentional changes from random fluctuations or other operations performed on the well. Using

autocorrelation, any variation of sufficient magnitude can be used to send commands by controlling, for example, the timing or number of repetitions in a sequence.

[0006] Advantages and other features of the invention will become apparent from the following description, drawings, and claims.

Brief Description of Drawings

[0007] Figure 1 is a schematic view of a downhole tool controller system constructed in accordance with the present invention.

[0008] Figure 2 is a block diagram showing the primary components of the controller of the downhole tool controller system of Figure 1.

[0009] Figure 3 is a schematic view of an embodiment of the downhole tool controller system of Figure 1 in which the signal source is a gas.

[0010] Figure 4 is a flowchart showing an operational sequence of the controller of the downhole tool controller system of Figure 1.

[0011] Figure 5 is a graph of an example signal recorded by the controller of the downhole tool controller system of Figure 1.

Detailed Description

[0012] Referring to Figure 1, a downhole tool controller system 10 comprises a controller 12 and a signal source 14. Signal source 14 is shown located at or near the surface, but may be placed in any convenient location in or around a well 16. In the embodiment shown, controller 12 is conveyed into well 16 by a tubing 18. The downhole portion of downhole tool controller system 10 may be conveyed by other means such as a wireline or coiled tubing. A downhole tool 20 is shown proximately located to controller 12, but may be variously located in well 16.

[0013] Signal source 14 is a device to create signals in well 16 that controller 12 can detect. Signal source 14 may be, without limitation, rig pumps used to create pressure sequences by pressuring a closed volume or by changing the flow rate of fluid past the top of well 16; an air

compressor, bottles of compressed gas, or liquid nitrogen pumping units for gas injection and release from well 16; a valve or set of valves that allow well 16 to alternately flow and be shut-in for certain desired periods; or simply the mechanical manipulation of the conveyance device on which downhole controller system 10 is mounted to vary, for example, the hydrostatic pressure on controller 12.

[0014] The signal sources listed are examples of devices that create pressure sequences. Pressure sequence devices are preferable, but the invention is not limited to those. For example, the invention also includes the use of acceleration, flow rate, weight, or stress/strain as control parameters. Signal source 14 can vary to produce those or other signal types.

[0015] Controller 12 (Figure 2) comprises nonvolatile memory 22, a microprocessor 24, a buffer 26, an analog-to-digital (A/D) converter 28, and a downhole tool interface 30. Those elements of controller 12 may be separate circuit elements or they may be combined in whole or in part in an integrated circuit.

[0016] Programmed instructions and reference parameters or criteria are stored in nonvolatile memory 22. Microprocessor 24 executes those programmed instructions and performs the necessary computation of parameters for comparison to corresponding reference parameters. Microprocessor 24 controls the timing of samples taken and storage of such sampled data in buffer 26.

[0017] Buffer 26 is random access memory (RAM) comprising various registers in which data values are sequentially stored. Buffer 26 may initially be set to zero and the registers filled one sample at a time. Each time a new sample is taken, the data stored in buffer 26 is shifted "upward" one register and the new data value is placed in the first or lowermost register. As the buffer receives a data sample, the "oldest" sample, which is stored in the last or highest most register, is allowed to "roll off" the buffer and the most recent data sample is stored in the first register. As explained below, buffer 26 is treated as though it has two halves, though it is preferably a single memory device.

[0018] A/D converter 28 takes an analog signal from a sensor and converts the analog signal to a digital signal, as is well known in the art. For example, the sensor may be a pressure

transducer that outputs an analog electrical signal in accordance with the sensed pressure. Converter 28 samples the analog signal and provides the digital sample to buffer 26. Other types of sensors may be used.

[0019] Downhole tool interface 30 is a device to perform some action that will initiate the actuation of downhole tool 20. Interface 30 awaits a command from microprocessor 24 before performing such action. Interface 30 may be, without limitation, a solenoid, a valve, a frangible element, a pyrotechnic, or a battery, depending on the requirements of downhole tool 20.

[0020] In operation, downhole controller system 10 is run into well 16 to some desired depth. System 10 is preferably run in on conventional tubing, but in some embodiments it may be run in using coiled tubing or slickline. For example, coiled tubing may be the conveyance mechanism of choice if flow rate is the key control parameter, *i.e.*, the signal. The rate at which fluid is delivered (volume of fluid per unit time) through the coiled tubing could be sensed by a spinner, a differential pressure gauge, or other means.

[0021] Similarly, system 10 may be deployed on a slickline. This may be preferable in the case in which acceleration is used as the control signal. The slickline could be jerked sharply in a pre-determined manner to induce accelerations that are sensed by an accelerometer or other device.

[0022] Returning to the embodiment in which conventional tubing conveys system 10 to the desired depth, Figure 3 shows an embodiment in which signal source 14 uses a gas to induce pressure pulses. Signal source 14 inputs a pressure signal into a gas layer 32. That signal is typically, though not necessarily, transferred into a liquid layer 34, where it is ultimately sensed by controller 12.

[0023] Controller 12 operates generally by performing the steps shown in Figure 4. Controller 12 begins its cycle by obtaining a pressure sample (element 36). Controller 12 shifts the data in buffer 26 "upward" in each register, discarding the data value in the last register and storing the newest data sample in the first register (element 38). Controller 12 computes parameter values using the data in buffer 26. For certain parameters, the first half of buffer 26

and the second half of buffer 26 are used separately (element 40). The two halves of buffer 26 may be used separately because the first half is used to define a command signal, and the second half is used to determine whether a command has been sent. For other parameters, the data in buffer 26 is used as a composite whole. The computed parameters are compared to reference values in various ways, depending on the particular parameter, to determine whether a match occurs (element 42). A "match" means the computed parameters are within pre-defined tolerances. If no match is found, the cycle is repeated. If a match is found, a command is sent to downhole tool interface 30 to actuate downhole tool 20 (element 44).

[0024] Different parameters can be used to decide whether a match has occurred. One such parameter is the normalized correlation coefficient between the two halves. Autocorrelation is a well known technique used in digital signal processing. It involves the comparison of a waveform against itself as one of the waveforms is shifted relative to the other. When the compared curves show no appreciable similarity, the normalized correlation coefficient will be nearly equal to zero. When the compared curves essentially align, the normalized correlation coefficient will be nearly equal to one. In the following description, the term "correlation coefficient" shall mean normalized correlation coefficient unless stated otherwise.

[0025] To further explain using an example, suppose buffer 26 has thirty-six registers, each register being able to store a data sample. Registers nineteen through thirty-six make up the first or upper half of buffer 26 and registers one through eighteen make up the second or lower half of buffer 26. Assume signal source 14 is a valve either allowing or preventing the flow of fluids from the well to the surface. Further assume the valve is changed from a closed state to an open state so that the fluid in well 16, initially at static equilibrium, is allowed to flow freely for some half-period $T/2$. During that half-period, registers one through nine store the sensed pressure at equal time intervals (according to some desired sample rate). A continuous plot showing the recorded waveform over the first half-period $T/2$ is shown in Figure 5. The pressure falls as the fluid flows, approaching dynamic equilibrium.

[0026] Further assume well 16 is shut in at the end of the first half-period, causing the fluid flow to cease. Assume the shut-in period is for a half-period $T/2$. As shown in Figure 5, pressure builds back toward static equilibrium. After a full period T , registers one through nine

will contain the waveform from the second half-period and registers ten through eighteen will contain the waveform from the first half-period. Each time before a new sample is taken, the waveform stored in registers one through eighteen is compared to the waveform stored in registers nineteen through thirty-six using a correlation coefficient.

[0027] The correlation coefficient is computed by first computing the mean or average of the curve for each full period. The mean for samples one through eighteen is computed by summing those sample values and dividing by eighteen. The mean for the upper half of buffer 26 is computed similarly. The next step in computing the correlation coefficient is to compute the difference between each sample value and the mean for that half of buffer 26. For example, the mean of the lower half of buffer 26 is subtracted from the sample value in register one, the mean of the lower half of buffer 26 is subtracted from the sample value in register two, and so on until the first eighteen differences are computed. The differences between the mean of the upper half of buffer 26 and registers nineteen through thirty-six are similarly calculated.

[0028] The differences of corresponding registers are then multiplied as pairs of factors. That is, the difference for register one is multiplied by the difference for register 19. The difference for register two is multiplied by the difference for register 20, and so on until a product is formed for each pair of difference for corresponding registers. Those products are then summed to produce a numerator. To achieve the normalization, that numerator must be divided by a normalization factor.

[0029] To compute the normalization factor, one uses the differences computed above. Each difference for the lower half of buffer 26 is squared and those squares are summed. Similarly, each difference for the upper half of buffer 26 is squared and those squares are summed. Those two sums are multiplied together and the square root of that product is taken. The resulting (positive) root is the normalization factor. Dividing the numerator computed above by the normalization factor yields the correlation coefficient.

[0030] Expressed as an equation, the correlation coefficient can be written as:

$$\frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2}}$$

where: x_i is a sample in the lower half of buffer 26;
 \bar{x} is the mean of the lower half of buffer 26;
 y_i is a sample in the upper half of buffer 26; and
 \bar{y} is the mean of the upper half of buffer 26.

[0031] Another parameter used to distinguish between noise and a command signal is the mean for each half of buffer 26. The difference of those means is computed and must be within some operator-defined maximum for the received input to be characterized as a command signal. This helps prevent a false characterization based solely on the correlation coefficient. For example, a straight line having a slope of one would yield a correlation coefficient of one, indicating the "curves" in each half of buffer 26 have identical shapes. However, the mean of the lower half of buffer 26 would be considerably less than the mean for the upper half. If the curves held in memory in each half of buffer 26 are truly similar, their means must also be very nearly the same, within some defined margin.

[0032] A further parameter used to distinguish a command signal is the standard deviation. The standard deviation indicates the way in which a function is centered around its mean, as is well known in the art. Again, one would expect the standard deviation of each half of buffer 26 to be nearly equal if the curves stored in each half are similar. Thus, their difference should lie within an operator-defined tolerance. Standard deviation can be used in this way to assist in the decision of whether the operator has issued a command. In addition, standard deviation may be used to assure the received signal has sufficient amplitude to be considered a command signal. By requiring the standard deviation to exceed some threshold value, small amplitude noise can be discriminated against.

[0033] As an example, though the invention is by no means limited to this case, assume an operator wishes to perforate two zones in sequence in a well already having a perforated first zone. This situation may arise in the re-working of a well, or it may arise when the first zone is

perforated using conventional techniques, but those techniques will not work to perforate the other zones because of the communication path created by the first set of perforations. The present invention make it possible to initiate two perforating tools using unique firing commands. To perforate the second zone, a pressure profile may be generated by shutting in the well for, say, ten minutes, then flowing the well for ten minutes. Alternatively, the pressure profile could be generated by changing between two choke settings in ten-minute intervals. The actual shape of the resulting pressure profile representing the present command signal is not important. What matters is that the pressure changes be of sufficient amplitude and occur at the expected ten-minute intervals. If this pressure profile is immediately repeated, the repeated sequence will match the command signal and controller 12 will cause the gun for the second zone to fire.

[0034] Similarly, the gun for the third zone can be fired by creating a new pressure profile, say, using 15-minute time intervals for the shut-in and flow intervals. The new pressure profile becomes the new command signal and, if immediately followed by the same pressure sequence, controller 12 will cause the gun for that zone to fire.

[0035] In the preceding description, directional terms, such as "upper," "lower," "vertical," "horizontal," etc., may have been used for reasons of convenience to describe an apparatus and its associated components. However, such orientations are not needed to practice the invention, and thus, other orientations are possible in other embodiments of the invention.

[0036] Although only a few example embodiments of the present invention are described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the example embodiments without materially departing from the novel teachings and advantages of this invention. Accordingly, all such modifications are intended to be included within the scope of this invention as defined in the following claims. It is the express intention of the applicant not to invoke 35 U.S.C. § 112, paragraph 6 for any limitations of any of the claims herein, except for those in which the claim expressly uses the words 'means for' together with an associated function.